// JOSA COMMUNICATION

Communications are short articles. Appropriate material for this section includes reports of incidental research results, comments on papers previously published, and short descriptions of theoretical and experimental techniques. Communications are handled much the same as regular articles. Galleys proofs are provided.

# Incorporation of intraocular scattering in schematic eye models

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Received March 22, 1985; accepted May 28, 1985

Beckmann's theory of scattering from rough surfaces is applied to obtain, from the experimental veiling glare functions, a diffuser that when placed at the pupil plane would produce the same scattering halo as the ocular media. This equivalent diffuser is introduced in a schematic eye model, and its influence on the point-spread function and the modulation-transfer function of the eye is analyzed.

## INTRODUCTION

The important influence of the intraocular scattering in vision has been stated in many studies.[1–6] That influence is especially considerable when there is a glare source in the visual field, since the scattering halo of the glare source can mask other objects. The effect of the intraocular scattering is also important in ocular laser surgery, and it is necessary to take it into account in dosimetry computations.

Most authors give the results of their intraocular scattering measurements as a veiling glare function, which is usually presented in the empirical form

$$L_{\text{eq}} = A \frac{E}{(\theta + \theta_0)^n}, \tag{1}$$

where $L_{\text{eq}}$ is the equivalent veiling luminance in candelas per square meter; $E$ the illuminance in the pupil plane produced by the glare source (in lux); $\theta$ is the angle of the glare source from the line of sight (in degrees); and $A$, $\theta_0$, and $n$ are empirical parameters. The retinal illuminance $E_r$ is related with $L_{\text{eq}}$ by the expression[2]

$$E_r = (1 - R) \frac{\pi n'^2}{4} \left(\frac{D}{f'}\right)^2 L_{\text{eq}}, \tag{2}$$

where $R$ is the factor of absorption of the ocular media ($R \cong 0.3$), $n'$ the refractive index of the vitreous ($n' = 1.336$), $D$ the pupil diameter, and $f'$ the focal length of the eye ($f' \cong 22$ mm).

Vos *et al.*[7] combined the aberrations of the eye and the veiling glare function to compute the light profiles of the foveal image of a point source. In the present Communication, that computation is made by introducing in a schematic eye model a Gaussian diffuser placed at the pupil plane that would produce the same scattering halo as the ocular media (see Fig. 1). In order to obtain the parameters defining this equivalent diffuser, a reformulation[8] of Beckmann's theory of scattering of electromagnetic waves from rough surfaces[9] is applied. The parameters are computed by fitting the theoretical scattering halo with the empirical veiling glare function.

## THE EQUIVALENT DIFFUSER

The scattering properties of a Gaussian diffusing surface (or Gaussian thin diffuser) are characterized by two parameters[9]: the standard deviation $\sigma_\varphi$ and the correlation length (grain radius) $r_0$ of the optical path difference (OPD). On the other hand, expression (1) suggests that the best fit between theoretical and empirical functions will be obtained with a Lorentzian theoretical halo. Thus it is assumed that the autocorrelation function of the OPD is the exponential $\exp(-r/r_0)$. Also, the slightly rough diffuser approximation ($k^2\sigma_\varphi{}^2 \ll 1$) is assumed, since the specular component is much greater than the scattering halo in the retinal image. With these assumptions, the mean intensity distribution $\langle I(\xi, \eta)\rangle$ at the focus plane (retina) of a point source is given by the expression[8,9]

$$\langle I(\xi, \eta)\rangle = \frac{S^2 n'^2}{\lambda^2 f'^2} E \exp(-k^2\sigma_\varphi{}^2) \times \left\{ F_0(\xi, \eta) + \frac{2\pi r_0{}^2 k^2 \sigma_\varphi{}^2}{S} \frac{1}{\left[1 + \frac{k^2 r_0{}^2(\xi^2 + \eta^2)}{f'^2}\right]^{3/2}} \right\}, \tag{3}$$

where $F_0(\xi, \eta)$ is the specular component [the point-spread function (PSF) without diffuser]; $k$ the wave number; $S$ the pupil area; $n'$ the refractive index; $f'$ the focal length; $\lambda$ the wavelength; and $\xi$, $\eta$ spatial coordinates. As $[(\xi^2 + \eta^2)/f'^2]^{1/2} \cong \theta$ (here $\theta$ is given in radians) for small angles, there is a considerable similarity between the empirical [Eq. (1)] and theoretical [second term of Eq. (3)] scattering halos. It must be noted that $\langle I(\xi, \eta)\rangle$ is the PSF in coherent illumination.

 

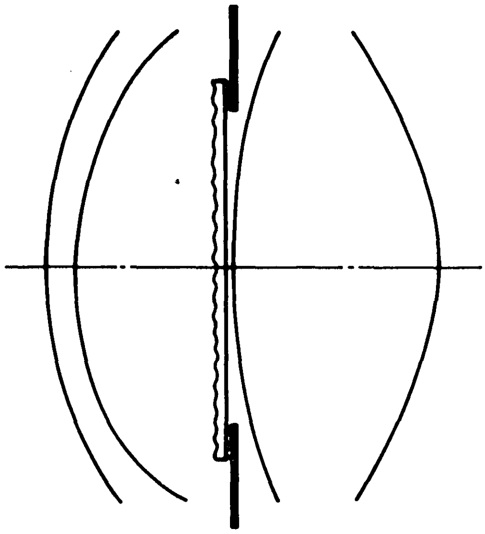

Fig. 1. Schematic eye with the equivalent diffuser.

Among the different veiling glare functions reported in the literature, those of Walraven[6] and Le Grand[2] have been chosen to compute the equivalent diffuser, Walraven's experimental veiling glare function being representative of the mean eye and that of Le Grand corresponding to a young subject (less than 30 years of age). Both veiling glare functions have been adjusted to the second term of Eq. (3). The results are summarized in Table 1, and the accuracy of the fit is shown in Fig. 2. The young eye has a $\sigma_\varphi$ half that of the mean eye owing to the known fact that the intraocular scattering increases with age.

## SCHEMATIC EYE AND EQUIVALENT DIFFUSER—INFLUENCE ON THE POINT-SPREAD FUNCTION MODULATION-TRANSFER FUNCTION

Once the intraocular scattering has been characterized by the equivalent diffuser, which is defined by only two parameters $\sigma_\varphi$ and $r_0$, it can be incorporated easily in schematic eye models (see Fig. 1). The monochromatic PSF of the schematic eye plus the equivalent diffuser is directly computed by expression (3), and the modulation-transfer function (MTF) by Fourier transform of that expression. After normalization, it becomes

$$T(u, v) = \frac{T_0(u, v) + \dfrac{4\pi^2\sigma_\varphi^2 f'^2}{S^2}\exp\left[-\dfrac{\lambda f'}{r_0}(u^2 + v^2)^{1/2}\right]}{1 + \dfrac{4\pi^2\sigma_\varphi^2 f'^2}{S^2}}, \tag{4}$$

where $u, v$ are spatial frequencies and $T_0(u, v)$ is the MTF of the optical system without diffuser.

The equivalent diffuser has been introduced in a schematic eye model[10] to compute the resulting PSF and MTF. The parameters of this schematic eye are listed in Table 2, and the resulting polychromatic PSF's,[10] with and without equivalent diffuser ($\sigma_\varphi = 0.05\ \mu$m, $r_0 = 32\ \mu$m) for several pupil diame-

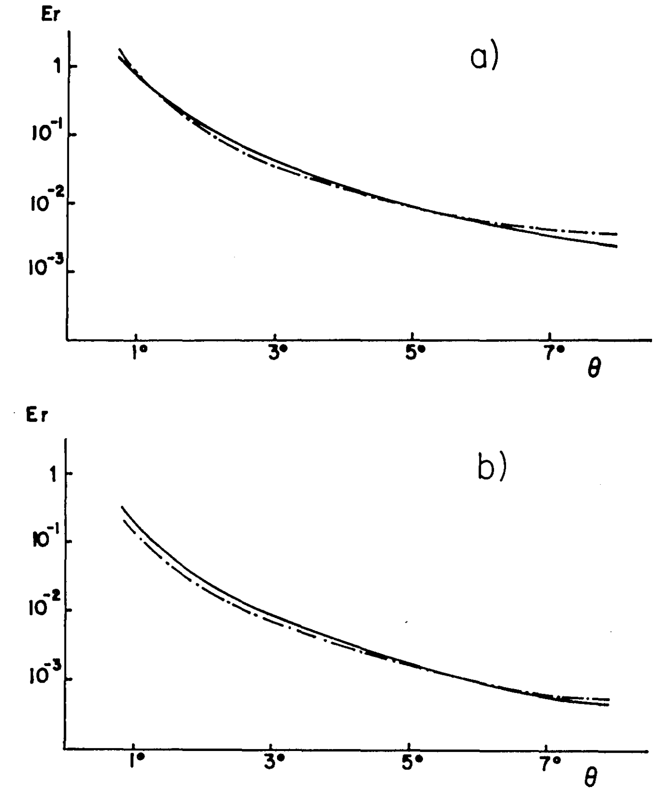


Fig. 2. Adjustment of the veiling glare functions of a) Walraven and b) Le Grand. The figures represent both the empirical functions (dashed lines) and the calculated scattering halos (continuous lines) of the equivalent diffusers. $E_r$ is the retinal illuminance normalized to the illuminance $E$ at the pupil plane.

**Table 1. Equivalent Diffuser Parameters, $\varphi_\varphi$ and $r_0$, Computed from the Veiling Glare Functions of Walraven and Le Grand**

| | Walraven (Mean Eye) | Le Grand (Young Eye) |
|---|---|---|
| Veiling glare function | $L_{eq} = \dfrac{29E}{(\theta + 0.13)^{2.8}}$ | $E_r = E\left(\dfrac{0.61}{\theta^3} + \dfrac{0.05}{\theta^{1.5}} + 0.0002 \cdot \cos^4\theta\right)$ |
| Validity range | $0.15° < \theta < 8°$ | $1° < \theta < 30°$ |
| Roughness $\sigma_\varphi$ | 0.05 $\mu$m | 0.025 $\mu$m |
| Grain radius $r_0$ | 32 $\mu$m | 7 $\mu$m |

**Table 2. Schematic Eye Parameters**

| | Radius (mm) | Asphericity | Thickness (mm) | Refractive Index |
|---|---|---|---|---|
| Cornea | 7.72 (anterior) | −0.26 | 0.55 | 1.376 |
| | 6.5 (posterior) | 0 | | |
| Aqueous | – | – | 3.05 | 1.3374 |
| Lens | 10.2 (anterior) | −3.1316 | 4 | 1.42 |
| | −6 (posterior) | −1 | | |
| Vitreous | – | – | 16.4 | 1.336 |
| | | Refracting power = 60.4 diopters | | |

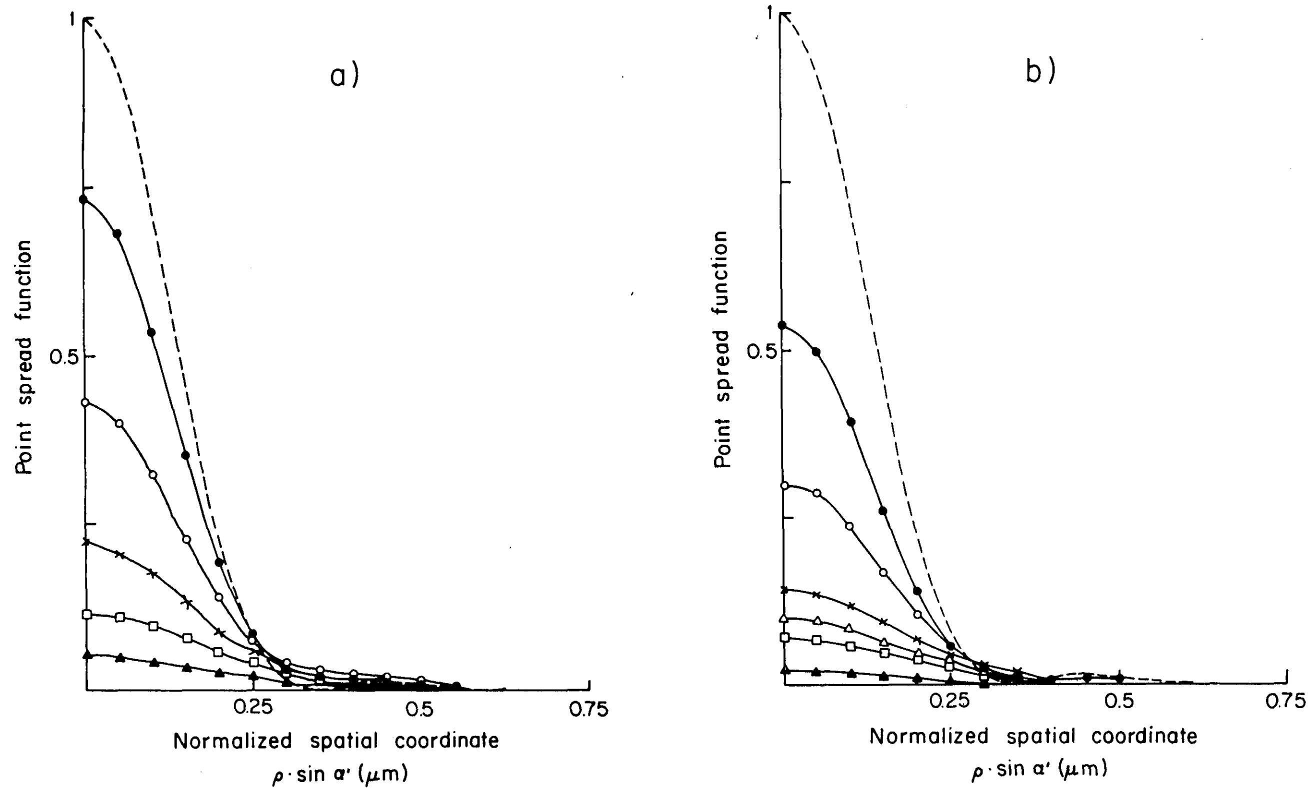


Fig. 3. PSF's of the schematic eye computed a) without and b) with the equivalent diffuser for several pupil diameters: 2 mm (●), 3 mm (○), 4 mm (×), 5 mm (△), 6 mm (□), and 8 mm (▲). $\rho$ is the radial coordinate (in micrometers) and $\alpha'$ the semiaperture angle. Dashed curve corresponds to the aberration-free system.

ters, are compared in Fig. 3. The factor $\exp(-k^2\sigma_\varphi^2)$ of expression (3) represents the fraction of light not scattered. Thus for the mean wavelength of the visible spectrum and normal incidence ($\lambda = 580$ nm), about 28% of the incident light is scattered for a mean eye, and about 7% for a young eye. However, the influence of the intraocular scattering on the MTF is negligible since the factor $4\pi^2\sigma_\varphi^2 f'^2/S^2$ is less than $10^{-4}$. That is reasonable because despite a considerable fraction of the incident light being scattered, this light spreads widely over the retina, and the intensity of the scattering halo is 4 orders of magnitude smaller than the specular component.

## SUMMARY

In this Communication Beckmann's theory of scattering of electromagnetic waves from rough surfaces is applied to intraocular scattering. It is shown that a thin Gaussian diffuser placed at the pupil plane reproduces, with good approximation, the experimental scattering halo (veiling glare function) produced by the optical media of the eye.

This equivalent diffuser can be introduced in schematic eye models in a simple way; only two parameters are needed. Thereby the schematic eye including the equivalent diffuser reproduces the PSF, retinal light profiles, and MTF of the mean eye.

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3. W. S. Stiles and B. H. Crawford, "The effect of a glaring light source on extrafoveal vision," Proc. R. Soc. London B **122,** 255–280 (1937).
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upon the apparent brightness of an object," J. Opt. Soc. Am. **43**, 189–195 (1953).

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6. J. Walraven, "Spatial characteristics of chromatic induction; the segregation of lateral effects from stray light artifacts," Vision Res. **13**, 1739–1753 (1973).
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8. P. J. Chandley and W. T. Welford, "A re-formulation of some results of P. Beckmann for scattering from rough surfaces," Opt. Quantum Electron. **7**, 393–397 (1975).
9. P. Beckmann, "The scattering of electromagnetic waves from rough surfaces," Prog. Opt. **6**, 55–59 (1967).
10. The schematic eye as well as the computing of the PSF is described in R. Navarro, J. Santamaría, and J. Bescós, "Accomodation-dependent model of the human eye with aspherics," J. Opt. Soc. Am. A **2**, 1273–1281 (1985).

# FEATURE CALENDAR—JOSA B

## *SOLID-STATE LASER MATERIALS*

This issue will feature current research on new solid-state lasers with emphasis on spectroscopic, kinetic, and physical characteristics of the working material.

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## *MATERIALS FOR OPTICAL PROCESSING*

Papers on photorefractive materials for use in spatial light modulators and holographic processing have been particularly sought. Papers on other relevant materials, such as those using resonant and nonresonant $\chi_3$ nonlinearities have also been solicited.

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## *OPTICAL COHERENT TRANSIENTS*

Articles describing the results of new research concerning, for example, picosecond and femtosecond studies, broad-bandwidth excitation, applications to optical storage or processing, the effect of intense laser fields on relaxation processes, or the use of coherent transients in high-resolution spectroscopy have been invited.

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## *INTERACTION OF ULTRAVIOLET LASERS WITH SURFACES*

Contributions have been solicited that emphasize the mechanisms underlying the physical and the chemical changes that occur when ultraviolet light irradiates surfaces, either in vacuum or at the gas-surface or liquid-surface interface.

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## *STIMULATED RAMAN SCATTERING AND OTHER NONLINEAR TECHNIQUES FOR LASER-BEAM CONTROL AND MODIFICATION*

**Paper Deadline: January 1, 1986**

This issue will feature recent research on nonlinear optics techniques, such as Raman and Brillouin scattering, for beam control and multiplexing of short-wavelength lasers.

FEATURE EDITOR

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## *THE GENERATION OF COHERENT XUV AND SOFT-X-RAY RADIATION*

**Paper Deadline: September 15, 1986**

This feature will emphasize the rapid development in techniques and studies concerning the generation of coherent XUV radiation.

FEATURE EDITORS

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# FEATURE CALENDAR—JOSA A

## *QUANTUM-LIMITED IMAGING AND IMAGE PROCESSING*

**Paper Deadline: April 15, 1986**

This issue will feature articles on recent advances in the theory, detection, and processing of quantum-limited images.

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## *METEOROLOGICAL OPTICS*

**Paper Deadline: May 15, 1986**

This feature, consolidating papers from the OSA topical meeting of the same name, will include rainbows, halos, glories, coronas, mirages, stellar twinkling, and any other naturally occurring optical phenomena visible to the unaided eye. A limited number of full-color photographs will appear with articles in this issue.

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# FEATURE CALENDAR—JOSA A

## *WAVE PROPAGATION AND SCATTERING IN RANDOM MEDIA*

This feature deals with topics such as mean-field calculations and measurements, calculation and measurement of field-correlation functions, rough-surface scattering, and theoretical formulations of electromagnetic theory.

## *MACHINE VISION*

Contributions of papers that address the topics of imaging sensors, digital-optical algorithms, and novel hardware modules and/or systems for machine vision have been invited.

## *PROPAGATION AND SCATTERING OF BEAM FIELDS*

Contributions have been sought on topics, such as the characterization of beams, beam-displacement and profile-deformation effects, propagation of beam fields through or along thin films, and scattering of beams by apertures or obstacles.

## *IMAGE SCIENCE*

This feature, coordinated with the ICO-sponsored conference Image Science '85, will emphasize fundamental aspects of image science (imaging methods, nonconventional imaging, etc.), image processing (optical, electronic, etc.), and image-quality evaluation and modeling.

## *APPLICATIONS OF COHERENCE AND STATISTICAL OPTICS*

**Paper Deadline: November 5, 1985**

This issue will feature papers on recent advances in optical coherence theory and statistical optics and their applications.

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## *COMPUTATIONAL APPROACHES TO COLOR VISION*

**Paper Deadline: March 1, 1986**

Contributions are invited for a feature on computational approaches to color vision and related topics, such as color constancy, simultaneous color contrast, and modes of appearance of colors.

FEATURE EDITOR

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*(continued overleaf)*

# TECHNICAL CALENDAR

## Meetings of the Optical Society of America

**1985**

*December 2–4* **OSA Topical Meeting on Optical Bistability,** Tucson, AZ.

**1986**

*February 24–26* **OSA/IEEE Conference on Optical Fiber Communication (OFC '86),** Atlanta, GA.

*February 26–28* **OSA/IEEE Topical Meeting on Integrated and Guided-Wave Optics (IGWO '86),** Atlanta, GA.

*March 24–26* **OSA Topical Meeting on Noninvasive Assessment of the Visual System,** Monterey, CA.

*March 24–27* **OSA Topical Meeting on Short Wavelength Coherent Radiation: Generation and Applications,** Monterey, CA. (Abstract deadline: December 6, 1985.)

*March 31–April 4* **OSA Spring '86,** Honolulu, HI. (Abstract deadline: November 22, 1985.)
—Topical Meeting on Holography (March 31–April 2).
—Topical Meeting on Quantum-Limited Imaging and Image Processing (March 31–April 2).
—Topical Meeting on Signal Recovery and Synthesis II (April 2–4).
—Topical Meeting on Meteorological Optics (April 3–4).

*May 27–30* ***International Conference on Optical and Millimeter Wave Propagation and Scattering in the Atmosphere,** Florence, Italy. (Abstract deadline: December 15, 1985.) Information: OIC/OMSPA, Via Gustavo Modena, 19-50121 Florence, Italy.

*June 4–6* **OSA Topical Meeting on Tunable Solid-State Lasers,** Welches, OR. (Abstract deadline: March 3, 1986.)

*June 9–13* **OSA/IEEE International Quantum Electronics Conference (IQEC '86),** San Francisco, CA. (Abstract deadline: January 6, 1986.)
**OSA/IEEE Conference on Lasers and Electro-Optics (CLEO '86),** San Francisco, CA. [Abstract deadline (North America): January 6, 1986. Abstract deadline (overseas): December 16, 1985.]

*June 16–19* **OSA Topical Meeting on Ultrafast Phenomena,** Snowmass, CO. (Abstract deadline: February 3, 1986.)

*July 7–11* ***International Optical Computing Conference (IOCC '86),** Jerusalem, Israel. Information: J. Sharmi, Department of E.E., Technion—Institute of Technology, Haifa 32000, Israel.

*September 8–12* ***Sixth International Symposium on Gas Flow and Chemical Lasers (GCL),** Jerusalem, Israel. Information: S. Rosenwaks, Symposium Chairman, Department of Physics, Ben-Gurion University, P.O. Box 653, 84150 Beer Sheva, Israel.

*October 7–9* ***Fourth International Conference on Optical Fiber Sensors (OFS '86),** Tokyo, Japan. (Abstract deadline: May 10, 1986.) Information: OFS '86 Secretariat, OITDA, 20th Mori Building, 7-4, Nishi-Shimbashi 2-chome, Minato-ku, Tokyo 105, Japan.

*October 20–22* **OSA Topical Meeting on Multiple Excitation of Atoms,** Seattle, WA.

*October 20–24* **OSA Annual Meeting,** Seattle, WA.

**1987**

*January 19–22* **Conference on Optical Fiber Communication/International Conference on Integrated Optics and Optical Fiber Communication (OFC/IOOC '87),** Reno, NV.

*April 27–May 1* **OSA/IEEE Conference on Lasers and Electro-optics (CLEO '87),** Baltimore, MD.

*August 23–28* ***Fourteenth ICO General Assembly,** Quebec, Canada.

*August 24–28* ***1987 International Conference on Fourier and Computerized Infrared Spectroscopy,** Vienna, Austria.

*October 19–23* **OSA Annual Meeting,** Rochester, NY.

**1988**

*January 4–7* **Conference on Optical Fiber Communication (OFC '88),** San Antonio, TX.

*April 25–29* **OSA/IEEE Conference on Lasers and Electro-optics (CLEO '85),** Anaheim, CA.

*Optical Society of America is a cooperating Society.

# ANNOUNCEMENTS

## OPTICS '86

### Scheveningen, The Netherlands, May 21–24, 1986

Optics '86 is sponsored by the Deutsche Gesellschaft für angewandte Optik, the Optical Group of the United Kingdom Institute of Physics, and The Netherlands Optical Commission and will be held at Scheveningen, The Netherlands, May 21–24, 1986. For more information, write to Dr. J. L. F. de Meijere, Oldelft, P.O. Box 72, 2600 MD Delft, The Netherlands. Phone: (015) 601901.

## Color in Computer Generated Displays

### Toronto, Ontario, Canada, June 19–20, 1986

The Canadian Society for Color will host the 1986 International Colour Association (AIC) Interim Meeting on Color in Computer Generated Displays at the Ryerson Polytechnical Institute, Toronto, Ontario, Canada, June 19–20, 1986. The AIC is an international organization comprised of national color societies and provides the forum for discussing and exchanging information on color. The aim of this interim meeting is to bring together the color science, technology, and graphic communities to discuss the state of the art in problems related to color and computer-generated displays. Topics to be discussed include human factors of color, color transfer between media, benefits and drawbacks of using color, new color-display technologies, calibration, graphic design, and application of color graphics in vision research. For more information write to Dr. Peter K. Kaiser, Department of Psychology, York University, North York, Ontario M3J 1P3, Canada. Phone: (416) 667-6335.

## Image Detection and Quality

### Paris, France, July 16–18, 1986

This international topical meeting on Image Detection and Quality will be held in Paris, July 16–18, 1986. The meeting is organized by the French Optical Society and cosponsored by the International Astronomical Union, the International Commission for Optics, the European Physical Society, the Société Française de Physique, the Société des Electriciens et Electroniciens, and the Deutsche Gesellschaft für Angewandte Optik. Topics to be covered include all physical principles of detection and related components and materials, such as electronic detectors, photochemical detectors, and electro-optic materials. Imaging methods and image processing will be considered only in relation to image detection. For more information, write to the Secrétariat exécutif, A.N.R.T., 101 Avenue Raymond Poincaré, Paris 75116, France.

## International Congress of Photographic Science

### Cologne, Germany, September 10, 1986

The next International Congress of Photographic Science (ICPS), organized by the Deutsche Gesellschaft für Photographie, will be held at the University of Cologne, Cologne, Germany, commencing September 10, 1986 and lasting about one week. This congress will be devoted, in general, to progress in basic principles of imaging systems and will cover the whole information chain from recording to display, including information processing in silver halides, nonsilver photochemical and physical materials, electronic imaging, and hybrid systems. It should be noted that emphasis will be on recent results, progress, and unsettled problems rather than on reviews of generally accepted facts. For more information write to E. Moisar, Deutsche Gesellschaft für Photographie, Oppenheimstrasse 16, D-5000 Köln 1, Germany. Phone: (0221) 739-1460.

## 14th General Assembly of the International Commission for Optics

### Québec City, Canada, August 23–28, 1987

The 14th General Assembly of the International Commission for Optics (ICO-14) will be held at the Québec Hilton International in Old City, Québec, Canada, August 23–28, 1987. ICO-14 is sponsored by the National Research Council of Canada and Université Laval with the Optical Society of America as a cooperating society. 1987's theme is the Optics and Information Age. The meeting will cover all aspects of optics, theoretical and applied, and will provide a special focus on the theme. For more information, write to Mr. L. Forget, Executive Secretary ICO-14, National Research Council of Canada, Ottawa K1A 0R6, Canada. Phone: (613) 993-9009. Telex: 053-3145.

# INVERSE PROBLEMS IN PROPAGATION AND SCATTERING

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